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Managing asset maintenance needs and reaching performance goals within budgets

Mikkel Bruun [a,*], Pascal Laumet [a]

[a]*AgileAssets Inc., 3001 Bee Cave Rd #200, Austin, TX 78746, United States*

Abstract

Maintenance condition surveys and quality assessments allow highway agencies to assess performance by calculating performance measures and tracking performance against annual maintenance expenditures. These performance assessments are often used as justification for adopting and implementing previous year work activities in the future and to identify areas of improvement.

However, this approach does not allow the asset manager to prioritize maintenance activities and justify investment across maintenance areas. While implementation of Maintenance Quality Assessment (MQA) programs is a necessary first step, several agencies in the United States are now starting to take the next step.

These agencies have started deploying a framework that helps identify the optimal set of roadway maintenance activities that should be done to improve performance given a certain budget. Their goal is to quantify the impact of various levels of funding in terms of network performance. The framework comprises of a set of performance measures that are calculated based on data collected during maintenance condition surveys, analytical models that allows for estimation of costs to achieve a certain desired level-of-service (LOS), and an integer programming based optimization model that helps in determining the best set of maintenance activities that can achieve performance goals given budget constraints. In this paper, a maintenance model for Network Maintenance Analysis is presented that is based on existing practice of using LOS and therefore can be easily incorporated into existing decision processes.

* Corresponding author. Tel.: +4553661966.
E-mail address: mbruun@agileassets.com

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1. Introduction

The majority of maintenance optimization literature is focused on pavement maintenance related to pavement management systems. The question of how properly to optimize the full range of typical highway maintenance activities based on measurement and prediction of performance is not well covered, and practitioners are only now getting started in this area using software tools to aid in planning non-pavement related maintenance.

While much of the optimization work to date focuses on predicting deterioration explicitly over time, this paper presents a method of maintenance optimization, here called maintenance analysis, which assumes a steady state is reached with regard to maintenance activities. The use of this maintenance analysis method allows maintenance managers to use levels of service (LOS) and utility functions to define maintenance indices. It thereby allows the manager to identify and plan the optimal mix of maintenance activities to maximize performance with respect to maintenance performance indices or minimize cost based on user defined budget constraints or LOS targets respectively.

A significant number of states conduct (or plan to conduct) maintenance condition surveys (MQA) and some have mature systems using LOS. Not many states are actively modelling the relationship between LOS and cost. Fewer still are actually using optimization to identify and plan the best possible mix of maintenance activities to maximize performance of their maintainable elements.

The question we are ultimately trying to answer is: What is the best set of LOS numbers to aim for given a certain budget scenario?

1.1. Finding the right mix

Since non-pavement related maintenance activities represent a significant portion of total highway agency budgets, finding the mix of highway maintenance activities that maximizes the performance of non-pavement asset types while recognizing budget constraints and agency strategic performance measures can help an agency use allocated funds in the most efficient manner possible and ultimately do more with less.

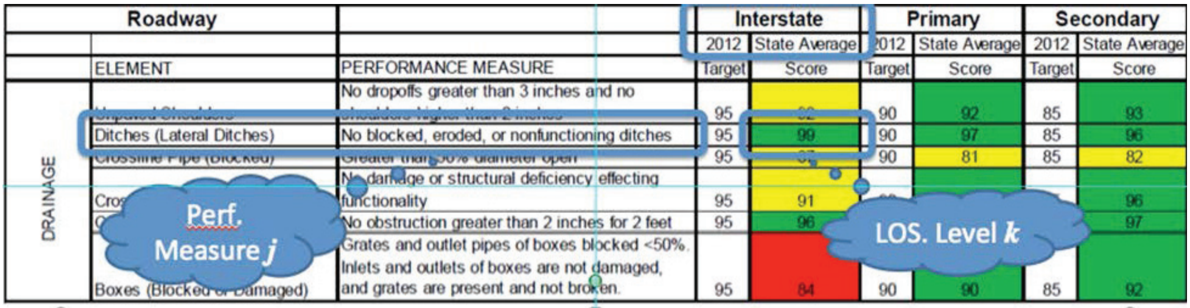
The majority of recent publications on optimization and analysis of highway maintenance are focused on pavement management systems (PMS). This is not surprising, since pavement maintenance represents a large portion of budgets managed by highway agencies. However, another essential part of highway maintenance, maintenance of roadside appurtenances and other non-pavement related assets such as signs, guardrails, pavement markings, etc., is not extensively covered.

The National Cooperative Highway Research Program, Synthesis 426, summarizing Performance-Based Highway Maintenance and Operations Management presented results of a national survey of practices used by various state departments of transport (DOTs). The survey revealed that a number of states conduct condition surveys and have mature systems using Levels of Service to steer their maintenance and operations efforts. However, it does not appear that many states are actively modelling the relationship between level of service (LOS) and cost, and even fewer still are actually using optimization to identify and plan the best possible mix of maintenance activities to maximize performance of their maintainable elements.

While not mentioned explicitly in the synthesis , a small number of state Departments of Transportation (DOTs) are pursuing the approach outlined in this paper and it is the intention of the authors to report on these efforts, using actual data from the agencies, in the future. The intention of this paper, however, is to introduce the concept and lay the foundation for this optimization analysis for maintenance activities.

To distinguish the analysis of maintenance activities on non-pavement asset types and roadside appurtenances (such as sign and guardrail maintenance) from pavement related preservation activities (such as surface seals), maintenance of roadside appurtenances is here referred to as Network Maintenance Analysis and defined as *a process that obtains the best possible LOS for a set of maintenance performance measures so that the overall performance of asset maintenance network is maximized given a limited budget and other constraints.* Conversely, it can also be the process by which the minimum budget is found to support LOS targets.

Unlike analysis that seeks a particular work plan for each asset in the network for future years, maintenance analysis operates at the maintenance activity level (not on the level of individual assets). This type of analysis also assumes a steady state within the network. The solution is of the form “to maintain an overall target maintenance performance index value of *Z*, county *A* needs to spend a certain amount continuously every year maintaining culverts, county *B* needs to spend a certain amount maintaining shoulders”.



Roadway			Interstate		Primary		Secondary	
			2012	State Average	2012	State Average	2012	State Average
	ELEMENT	PERFORMANCE MEASURE	Target	Score	Target	Score	Target	Score
DRAINAGE	Unpaved Shoulders	No dropoffs greater than 3 inches and no shoulders higher than 2 inches	95	[illegible]	90	92	85	93
	Ditches (Lateral Ditches)	No blocked, eroded, or nonfunctioning ditches	95	99	90	97	85	96
	Crossline Pipe (Blocked)	Greater than 50% diameter open	95	[illegible]	90	81	85	82
	Cros[illegible]	No damage or structural deficiency effecting functionality	95	91	[illegible]	[illegible]	[illegible]	96
	[illegible]	No obstruction greater than 2 inches for 2 feet	95	96	[illegible]	[illegible]	[illegible]	97
	Boxes (Blocked or Damaged)	Grates and outlet pipes of boxes blocked <50%. Inlets and outlets of boxes are not damaged, and grates are present and not broken.	95	84	90	90	85	92

Fig. 1. Example of elements for assessing budgets. Note that Scores (LOS values) are per Performance Measure and per ‘Cell’ – e.g. Road Class and County.

2. Model Formulation

Consider the asset network as a set of assets with different associated *performance measures* (*P*). For example, the road surface, culverts, and signs result in different *P*’s of the road network. Assume there are M different *P*’s under consideration.

Further, the asset network is divided into cells of individual geographical or jurisdictional areas. For instance, districts or county or maintenance sections can be cells. Additional subdivisions can be created by including other attributes such as functional class of roads, traffic levels, climate zones or environmental characteristics. Division is done according to performance based planning needs. Let us assume there are *N* cells in the network.

2.1. Performance per "cell"

The following attributes are known for each cell:

1. m_{ij} – the measure or indication of quantity of the asset type associated with each performance measure, j, in every cell, i.

2. k_{ij}^{curr} – the level of service (LOS) or performance level currently achieved for each P_j in every cell i. This measure k_{ij} can be presented as the percent of assets above a certain minimum condition threshold (percent passing) among all assets surveyed, or any other numeric attribute that represents the LOS for the cell. It would typically be derived from a condition survey of this P_j in the cell. Each P_j can have L_j possible LOS values. For instance, percent passing for signs might have 100 levels and condition state for road surface may have 5 levels [A, B, C, D, F], etc. For instance, with reference to Exhibit 5 from NCHRP 426 (4) giving Washington States metrics for Catch Basins and Inlets from their MAP Manual, if it was desired to measure and track Catch Basin and Inlet performance using percent failed directly, then there would be 100 different levels ($L_j = 100$). However, as is actually the case, these percent failed values are further translated into Service Levels, A, B, C, D and F respectively, in which case the analysis would be conducted using 5 levels ($L_j = 5$).

3. c_{ij}^{curr} – the annual spending to support the current LOS for each P_j in each cell.

To represent aggregated LOS over several cells, the weighted average of k proportional to m is used. For example, for any defined set of cells A within the network (for instance, an entire District or a specific Functional

Class), let k_j^A for P_j be the average of k_{ij} across all cells in the set A, weighted by the relative measure of P_j across all cells in A, i.e.:

$$k_j^A = \frac{\sum_{i \in A} m_{ij} k_{ij}}{\sum_{i \in A} m_{ij}} \text{ or for the whole network: } k_j = \frac{\sum_{i=1}^{N} m_{ij} k_{ij}}{\sum_{i=1}^{N} m_{ij}}. \tag{1}$$

Additionally, as discussed below, we assume that the function that gives the budget required to move from the current LOS level to the target level is known. Denote this function $f_{ij}(k_{ij}, t_{ij})$, where t_{ij} is a target LOS that is set for P_j in cell *i*. With this function $c_{ij}(k_{ij})$, the cost of providing target LOS t_{ij} for P_j for cell *i* can be calculated using:

$$c_{ij}(k_{ij}) = c_{ij}^{curr} f_{ij}(k_{ij}^{curr}, t_{ij}) \tag{2}$$

2.2. LOS levels and costs - examples

There are various ways of defining the relationship between budget and LOS for each performance measure in each cell and while it is the intention of the authors to report on work in this area in the future, it is not intended to discuss this at length in this paper but rather to elucidate an optimization analysis framework that can be used with any identified function. Nonetheless, a couple of approaches are very briefly introduced below, one of which is used in the numerical example given later in this paper.

In one example approach, a two-stage Markov Cost Model can be used to define the shape of LOS to cost function f_{ij}. In a steady state, the percentage of failed asset inventory with respect to any P_j can be assumed to be constant if the rate at which assets are restored to the non-failed state by maintenance matches the rate at which the assets are failing (moving from the non-failed state to a failed state by falling below the defined threshold level). The average total number of assets failing per unit time is thus dependent on the proportion of elements in the non-failed state and the probability of failure: the more there are in the non-failed state, the higher the number of failures per unit time and the greater the maintenance effort needed to repair these failures and maintain that proportion. For steady state, therefore, this can be characterized as:

$$p\lambda = q\mu, \tag{3}$$

where p and q are the fraction of the total assets in the non-failed and failed states, respectively, such that $p + q = 1$; λ is the probability of failure or rate of failure per unit of non-failed assets; μ is the probability of maintenance or rate of maintenance per unit of failed inventory.

In some cases the service rate μ is the limiting factor and the cost model is exponential. This implies that to increase the fraction of assets in the non-failed state, the number of resources (often employees but sometimes equipment such as snow removal equipment) must be increased. This would occur if the time allocated to the activity was restricted to a fixed amount and/or the response time was part of the performance measure.

In this case, it is assumed that in order to change the equilibrium and increase the fraction of assets in a non-failed state to p', this will require a change (increase) in the service rate μ to μ'. Assume now that the ratio of the extra effort in terms of extra resources required to the original effort is μ' / μ .

Using the steady state equation and assuming that λ remains unchanged, this ratio is equal to

$$\frac{\mu'}{\mu} = [\frac{1}{q'} - 1][\frac{q}{1-q}] \tag{4}$$

This implies that if μ' is plotted against q' the result is that μ' approaches infinity as q' tends to zero. This further implies that the cost becomes exponentially higher as the proportion of failed assets is reduced to near zero. This makes intuitive sense in that costs would be impossibly high to keep everything in perfect shape at all times. On the other hand, the cost tends to zero as q' is allowed to approach unity. In other words, it costs nothing to allow all assets to remain in a failed state.

In other cases, in a much simpler scenario we can assume the time allocated to serving the queue of failed assets can be varied. In this case the effort itself can be varied rather than just the rate of service and the same number of resources (typically employees as before but can also be contract work etc.) can be used but they need to spend more time performing this particular activity and can therefore accomplish more.

In this case, because the total quantity of work accomplished is being varied, the ratio of the extra effort to the original effort is $p'\mu'/p\mu$. Again, using the steady state equation this leads to:

$$p'\mu'/p\mu = q'/q \tag{5}$$

Under this scenario, assuming λ is a constant, this implies that if effort (cost) is plotted against p (proportion in non-failed state, or LOS), the function is linear (until the boundary $p'= 1$ is reached). This also makes intuitive sense in this case since, if assets are found to fail at a constant rate, then if the frequency for an activity such as mowing grass is doubled, then the proportion of grass area in a failed state is halved.

The maintenance analysis problem is to find k_{ij}, the performance level in each cell, so that the total Maintenance Index (estimate of total maintenance quality) is maximized, subject to budget restrictions (or conversely, the budget is minimized subject to total maintenance index restrictions). Assume the Maintenance Index is a combination of LOS Utility functions $U_j(k_{ij}), j = 1,..., M$ and reflects the contribution of individual LOSs to the overall quality of network maintenance. Using a utility function can convert a linear LOS scale into non-linear representation reflecting the actual benefit value of a particular LOS to the maintenance manager and/or the general public. In the trivial case, assume $U_j(k) = a_j k$, i.e. the function is linear with the coefficient a_j representing the relative importance of the LOS for P_j in the overall maintenance index. The maintenance analysis problem is then formulated as:

$$\begin{aligned}
&\max_k \sum_{i=1}^{N}\sum_{j=1}^{M} \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} U_j(k_{ij}) \\
&s.t. \quad \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij}(k_{ij}) \le C \\
&\qquad k_{ij} \in L_j,\ j = 1,\ldots,M,\ i = 1,\ldots,N
\end{aligned} \tag{6}$$

or conversely:

$$\begin{aligned}
&\min_k \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij}(k_{ij}) \\
&s.t. \quad \sum_{i=1}^{N}\sum_{j=1}^{M} \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} U_j(k_{ij}) \ge U \\
&\qquad k_{ij} \in L_j,\ j = 1,\ldots,M,\ i = 1,\ldots,N
\end{aligned} \tag{7}$$

This problem is not linear but an approximate solution can be found using the incremental benefit cost ratio method. Denote $\Delta U_{ij}\left(k_{ij}\right) = U_j\left(k_{ij}\right) - U_j(k_{ij-1})$ as the increase in utility that level k_{ij} gives over the previous level $k_{ij} - 1$, and $\Delta c_{ij}\left(k_{ij}\right) = c_{ij}\left(k_{ij}\right) - c_{ij}\left(k_{ij} - 1\right)$ as increase in cost to move to the level k_{ij} from $k_{ij} - 1$.

The incremental benefit cost ratio method can be performed by considering a sequence of $\{i,j\}$ ordered by values: $\Delta U_{ij}(k_{ij})/\Delta c_{ij}(k_{ij})$ and going through this sequence accumulating total costs C_{ij}^{accum} and utility values U_{ij}^{accum} until a constraint is satisfied for the first time. For this sequence, the accumulated values $\{U_{ij}^{accum}, C_{ij}^{accum}\}$ represent points on the efficient frontier where each point is an optimal solution. Such an efficient frontier is useful because it gives a general idea of what maintenance index value can be achieved for certain budget levels. However, as a method for solving the general maintenance analysis problem it has three main drawbacks:

1. A key assumption of this method is that the incremental gain in utility function is more costly for higher levels of service. In other words: $\Delta U_{ij}(k_{ij})/\Delta c_{ij}(k_{ij}) > \Delta U_{ij}(k_{ij}+1)/\Delta c_{ij}(k_{ij}+1)$. While commonly the case, this assumption is not always true.

2. This method does not give an exact solution if the constraint is not exactly equal to one of the accumulated values.

3. Most importantly, the method works with one constraint only.

In order to overcome these disadvantages we reformulate the maintenance analysis problem as a binary programming problem (an integer programming problem where decision variables can be only 0 or 1). In this case the decision variables are x_{ijk} (i network cell, j performance measure, k LOS). If the solution has $x_{ijk} = 1$ this indicates that for performance measure j in cell i, the optimum LOS is k. Because for each cell i and performance measure j, only one LOS value can be selected as a target level, there are always the constraints:

$$\sum_{k=1}^{L_j} x_{ijk} = 1, i = 1, \dots, N, j = 1, \dots, M \tag{8}$$

Given our previous assumptions and formulation, at least three different objectives can now be considered:

A. Minimize the total maintenance budget as the objective:

$$\min_x \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{L_j} c_{ij}(k_{ij})\, x_{ijk} \tag{9}$$

B. Maximize a basic maintenance index for the network which is a linear combination of network LOS's for all defects with weights a_j:

$$\max_x \sum_{j=1}^{M} a_j \sum_{i=1}^{N} \sum_{k=1}^{L_j} \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} k x_{ijk} \tag{10}$$

C. Maximize the overall utility rather than using the basic maintenance index based on the simple performance levels:

$$\max_x \sum_{j=1}^{M} a_j \sum_{i=1}^{N} \sum_{k=1}^{L_j} \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} U_j(k) x_{ijk} \tag{11}$$

The corresponding constraints can have the same form as the objectives above with the right hand side being the maximum allowed budget or the minimum allowed maintenance index or utility. The constraints can also be separate for different areas of the network as well as for different sets of performance measures. For example one might want to separate the maintenance budget for interstate highways (IHS) from the budget for other roads or/and ensure that the quality of maintenance for the road surface performance measure is not below a specified threshold. In this case the problem can be formulated as:

$$\begin{aligned}
&\max_{x} \sum_{j=1}^{M} a_j \sum_{i=1}^{N} \sum_{k=1}^{L_j} \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} U_j(k) x_{ijk} \\
&s.t. \quad \sum_{i\in IHS} \sum_{j=1}^{M} \sum_{k=1}^{L_j} c_{ij}(k) x_{ijk} \le B_{IHS} \\
&\sum_{i\notin IHS} \sum_{j=1}^{M} \sum_{k=1}^{L_j} c_{ij}(k) x_{ijk} \le B_{other} \\
&\sum_{i=1}^{N} \sum_{j\in S} \sum_{k=1}^{L_j} a_j^* \frac{m_{ij}}{\sum_{l=1}^{N} m_{lj}} U_j(k) x_{ijk} \ge I_{RS} \\
&x_{ijk} - bin,\ j = 1,\dots,M,\ i = 1,\dots,N,\ k = 1,\dots,L_j
\end{aligned} \tag{12}$$

where set S is a set of P_j's that form the maintenance index for the road surface, B_{IHS} and B_{other} are the budgets for interstate highways and other roads respectively, I_{RS} is the target maintenance index, and a_j^* is a normalized coefficient associated with P_j in the road surface maintenance quality index such that $\sum_{j\in S} a_j^*=1$.

In general, every constraint c has a valid scope $\{i,j\}^c$ that is some subset of the full $\{i,j\}$ $i=1,\dots N$, $j=1,\dots,M$ set. Each constraint also has a type (it is either a budget constraint or a performance constraint) and the right hand side (RHS) is also specified in that it is either the maximum allowed budget or the minimum allowed performance. We can also consider constraints for the percentage of cells that fall below a threshold K_j in maintaining some P_j.

3. Numerical Example

The maintenance analysis method described above is illustrated in the following numerical example. In order to be able to easily see the result of the optimization, we set N, the number of cells in the network, to 2. The number of performance measures P considered is 10: Unpaved Shoulders, Long Line Pavement Markings, etc. Table 1 shows the full list of performance measures. Every P_j is ranked on 1-5 scale.

Table 1. List of P_j's.

P_j ID	P_j Name
1	Unpaved Shoulders
2	Ditches (Lateral Ditches)
3	Crossline Pipes (Blocked)
4	Crossline Pipes (Damaged)
5	Curb & Gutter (Blocked)
6	Boxes (Blocked or Damaged)
7	Vegetation (Brush & Tree)
8	Vegetation (Turf Condition)
9	Long Line Pavement Markings
10	Words and Symbols

In order to be able to calculate the cost of transition from one LOS level to another we computed all possible values that function $f_{ij}(k_{ij}^{curr}, k_{ij})$ can take. In our example $f_{ij}(k_{ij}^{curr}, k_{ij})$ was based on the exponential variant of two-stage Markov cost model, see Formula 1.

Table 2 shows the transition coefficients for P_1, the “Unpaved Shoulders” performance measure, when going from the current LOS of 3 to the other 5 levels. For example, to compute the cost for an LOS target of 5 given the current level is 3 and last year $ 3000 was spent to support that level of 3, one needs to multiply 3000 by 5.828.

Table 2. Values of $\boldsymbol{f_{ij}(k_{ij}^{curr}, k_{ij})}$.

Pj ID	k_{ij}^{curr}	k_{ij}	$f_{ij}(k_{ij}^{curr}, k_{ij})$
1	3	5	5.828
1	3	4	1.718
1	3	3	1.000
1	3	2	0.681
1	3	1	0.098

The objective function used is the average utility across all P_j's, hence, $a_j = 1/10$ for $j = 1,...,10$. The utility functions are the same for every P_j and defined by equation 2. This form of the utility function was chosen to produce a balance across all P_j's maintenance plan.

$$U(k) = \begin{cases} -5, & if\ k \in (0,1) \\ 0, & if\ k \in (1,2) \\ k, & if\ k \in (2,3) \\ k+1, & if\ k \in (3,4) \\ 5 & if\ k \in (4,5) \end{cases} \tag{13}$$

Asset quantities and corresponding weights m_{ij} for each cell can be found in Table 3. Assuming the available budget B for the next year is \$525,000 and last year budget was \$484,012. The average performance level at optimality is 3.9. In comparison, last year's average grade is just 3.1 (since the optimization model was not used last year). The budget redistribution and observed LOSs can be found in Table 3 as well as those projected for the next year.

Table 3. Current and Target budget distributions.

Cell ID	P_j ID	Inv	m_{ij}	Cur Score	Cur Cost	Score	Target Cost
2	1	16060	1.000	2	$50,983	2	$50,983
1	2	991	0.589	4	$8,835	4	$8,835
2	2	691	0.411	4	$68,112	4	$68,112
1	3	60	0.034	1	$5	5	$94
2	3	1728	0.966	1	$27	4	$231
1	4	60	0.096	4	$5	4	$5
2	4	569	0.904	1	$27	4	$109
1	5	30989	1.000	4	$18,022	4	$18,022
1	6	9158	0.405	5	$44	5	$44
2	6	13433	0.595	1	$63	4	$254
1	7	31981	0.313	5	$15,002	5	$15,002
2	7	70079	0.687	4	$51,744	4	$51,744
1	8	39710	0.402	1	$14,418	4	$79,909
2	8	59105	0.598	4	$98,954	4	$98,954
1	9	60	0.018	5	$43,716	3	$16,265
2	9	3213	0.982	5	$114,048	5	$114,048
1	10	672	1.000	4	$7	4	$7

Table 4 has the performance levels from the previous year and the optimal objective performance levels. As one can see from Table 4, in order to improve the objective, the funds for Long Line Pavement Markings ($P_j = 9$) were cut and redistributed among other assets. It can be seen from Table 3 that for Long Line Pavement Markings (P_9) in cell 1, the weight is just 0.018 compared to 0.982 for cell 2. As a result, since the weight is so low, funds were cut from cell 1 while funds were increased to cell 2. This results in a moderate decrease in performance for cell 1, but this decrease is more than made up for by the increases elsewhere resulting from the redistribution of funds.

Table 4. Index by components.

P_j ID	1	2	3	4	5	6	7	8	9	10	Rating
Original	2.00	4.00	1.00	1.29	4.00	2.62	4.31	2.79	5.00	4.00	3.10
Optimal	2.00	4.00	4.03	4.00	4.00	4.41	4.31	4.00	4.96	4.00	3.97
Cost Diff	0	0	293	82	0	191	0	65491	-27451	0	38606

4. Conclusions

The majority of maintenance optimization literature is focused on pavement management maintenance treatments. The question of how properly to model deterioration and maintenance of roadside appurtenances is not extensively covered. It is shown in NCHRP 426, a synthesis of current practice of Performance-Based Highway Maintenance and Operations Management among state departments of transport (Markow, 2012), that a number of states conduct condition surveys and have mature systems using Levels of Service to steer their maintenance and operations efforts. However, it does not appear that many states are actively modelling the relationship between LOS and cost, and even fewer still are actually using optimization to identify and plan the best possible mix of maintenance activities to maximize performance of their maintainable elements. We believe that the optimization model presented in this paper, and currently being developed in a number of state agencies, for Maintenance Analysis contributes to this effort and shows how performance may be optimized subject to either budget constraints or level of service targets.

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